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LIBRATION ORBIT ECLIPSE AVOIDANCE MANEUVER STUDY FOR THE JAMES WEBB SPACE TELESCOPE MISSION

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Mission analysis of libration orbit trajectories at Sun-Earth/Moon L2 typically includes predictions of lunar and Earth eclipses during the mission life-time. The NASA James Webb Space Telescope (JWST) trajectory, by design, avoids these eclipses by pruning its launch window. In an off-nominal scenario where an eclipse is predicted, a maneuver strategy is needed. In this paper, trade studies are examined for JWST that characterize the burn magnitude, location, and epochs of multiple maneuver plans to avoid an eclipse. The results enable analysts to explore the space of feasible maneuver strategies during routine operations.

INTRODUCTION

Ensuring mission success of a spacecraft trajectory design depends on measuring key performance parameters that are linked to spacecraft system level requirements. Traditionally for Sun-Earth/Moon (SEM) libration point orbiters, requirements pertain to eclipse avoidance and Sun interference and are defined as the duration(s) within the mission lifetime that a spacecraft is allowed to pass through regions defined relative to the Sun, Earth, Moon, and other celestial bodies. Trajectories which violate these requirements can negatively impact spacecraft power, communication, and/or thermal subsystem hardware performance. For libration point orbiting missions, the L1 and L2 Lagrange points drive different trajectory design strategies: L1-orbiting spacecraft require avoidance of radio interference with Earth ground systems due to the Sun, while L2 spacecraft often require eclipse avoidance to meet thermal and power limitations due to the lack of sunlight on the spacecraft.

The James Webb Space Telescope (JWST) is an NASA astronomical observatory that is expected to launch in March 2021 with a direct insertion to a L2 SEM libration point orbit. In an off-nominal scenario where any duration of Earth or Moon eclipse is predicted post launch, a maneuver strategy is needed to avoid the shadow. This paper studies the feasibility that JWST can find a maneuver strategy to successfully avoid an eclipse. The paper first formulates the study by replicating prior avoidance strategies of operational spacecraft. Then it provides trade studies for a generic SEM L2 spacecraft in an example JWST orbit that characterize the burn magnitude, location, and epochs of multiple maneuvers to avoid an eclipse and maintain the libration orbit. Finally, it applies the JWST specific case to these studies. The results enable analysts to explore the space of feasible maneuver strategies during JWST routine operations for eclipse avoidance.

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BACKGROUND

The James Webb Space Telescope (JWST) is an NASA observatory spacecraft that will observe astronomical phenomena in the near to mid infrared spectrum in the exploration of dark matter, first light from galaxies, exoplanets, and other astronomy research topics. It will launch on an Ariane 5 from Kourou, French Guiana. To achieve the operational SEM L2 libration point trajectory, the spacecraft will perform 3 Mid-Course Correction (MCC) maneuvers within the first 30 days to establish the science orbit.¹ To maintain the orbit, JWST will perform station keeping maneuvers for an expected mission lifetime of 10.5 years. The total delta-V (dV) budget for the mission is approximately 113 m/s, with 25 m/s budgeted for station keeping.² An example image of the spacecraft is seen in Figure 1*. The JWST spacecraft is 6310 kg in mass and has a solar shield area of 161 m² when fully deployed. This section will focus on defining a JWST case study orbit with an Earth/Moon eclipse and then conclude with an overview of JWST maneuver direction constraints.

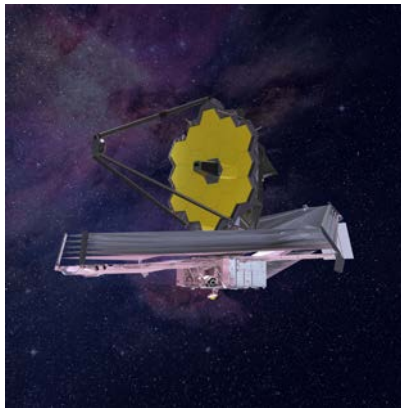


Figure 1. Artist Rendition of JWST.

Earth/Moon Eclipses in Libration Point Orbits

The definition of an eclipse from the Sun to a celestial body is shown in Figure 2[†]. All penumbral, umbral and annular regions are considered eclipse regions for JWST. The figure is relative to a vector defined by the center of the Sun to the center of the body.

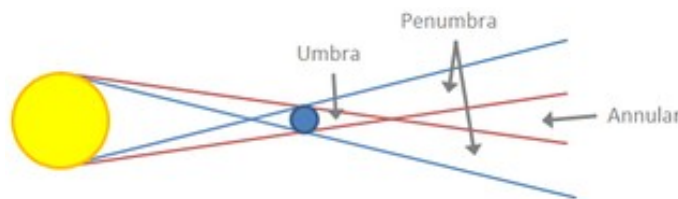


Figure 2. Definition of Eclipse between the Sun and the Earth or Moon (Not to Scale)

Thermal and power requirements state that the JWST mission shall not experience any Earth or Moon eclipses during its entire mission lifetime. By design, launch epochs for JWST are selected so that the nominal direct-insertion trajectory will not pass through any type of eclipse, starting with launch and continuing for 10.5 years of mission life. The trajectory is designed to accommodate 3-sigma launch vehicle dispersions, maneuver modeling and orbit determination errors while maintaining orbit near SEM L2. A major trajectory design driver is the requirement to maximize launch opportunities, both daily launch window duration

*<https://jwst.nasa.gov/images.html>

†<https://ai-solutions.com/freelyer/freelyer-software-help-desk/>

and number of days per month; therefore the acceptable JWST trajectories range from quasi-halo to Lissajous orbits about SEM L2. There is the remote possibility that greater than 3-sigma launch vehicle dispersions or other spacecraft contingencies significantly affecting the trajectory could cause the eclipse requirement to be violated. While this design strategy prevents encountering eclipses during the transfer trajectory, low probability scenarios with an eclipse occurring in the science orbit are possible. Greater than 3-sigma launch vehicle dispersions or other operations contingency scenarios could result in an eclipse from the Moon during the first 10.5 years. Changing science requirements which require orbit resizing during routine operations may bring an eclipse into existence. An extended mission beyond the 10.5 year mission lifetime goal could experience eclipse(s) if the initial orbit achieved is a closing Lissajous (collapsing towards the ecliptic plane). This analysis for JWST follows multiple studies for Earth/Moon eclipse avoidance in libration point orbit missions. These include analytical formulations,⁴ spacecraft operations of eclipse avoidance,⁵⁻⁸ and general system level studies on the topic.⁹

Baseline Trajectory Case

A JWST trajectory case generated during JWST launch window analysis that violates the eclipse requirement was selected; the eclipse from the Moon occurs about a year into the mission and would normally be rejected during the launch window analysis. This launch case was chosen to have a single penumbra/umbra eclipse event in its 10.5 year trajectory, preventing the use of any libration orbit families that repeatedly cause eclipses within the mission lifetime. It is also observed that these trajectories have annual seasonal behaviors that can be utilized in future launch opportunities¹⁰. The trajectory chosen for this study is seen in Figure 3 in the SEM Rotating Libration Point (RLP) frame. The RLP frame is centered at L2. The +RLP-X axis is defined by the vector from the Sun to Earth/Moon barycenter, and is into the page in Figure 3. The +RLP-Z component is along the angular momentum unit vector of the Earth/Moon barycenter's heliocentric orbit, the vertical axis in Figure 3. The +RLP-Y is the right-hand complement of the Z and X axes, in the direction of Earth's motion about the Sun, shown as the horizontal axis. To accompany Figure 3, properties of this JWST orbit are displayed in Table 1.

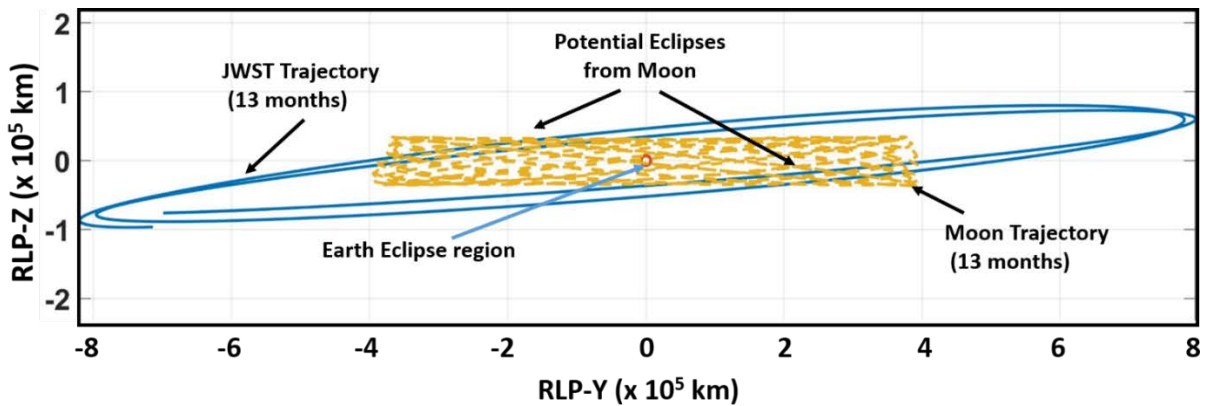


Figure 3. JWST Baseline 13 Month Orbit Position in the RLP-YZ Plane.

Table 1. JWST Baseline Orbit Case with an Eclipse Violation.

Orbit Event	Start Epoch (UTC)	End Epoch (UTC)	Delta V (m/s)
Launch	10/02/2018 11:45:00	--	--

Propagation Span	11/06/2018 20:46:46	12/05/2019 20:46:46	--
SK Maneuver 1	01/07/2019 01:47:03	Impulsive	0.05
EA Maneuver	01/29/2019 16:26:33	Impulsive	0
SK Maneuver 2	04/05/2019 16:34:20	Impulsive	0.06
Moon Eclipse	09/22/2019 01:17:13	09/22/2019 15:23:56	--
Total Delta V	--	--	0.11

With the RLP-X axis aligned approximately with the Sun-Earth line, the Earth projects a near-circular shadow of about 0.5 deg diameter at L2, shown as a red circle in Figure 3. The Moon projects an elliptical penumbra that precesses with time based on the Moon trajectory; however, since the Moon to L2 distance varies as the Moon orbits the Earth, the projection of the Moon disk onto the RLP-YZ plane varies from 0.1 to 0.2 deg in diameter. This creates a penumbra at the JWST orbit of only 4 to 12%, which could still affect the Observatory's ability to maintain the 40 deg Kelvin required for optimal science instrument operation. The JWST trajectory in Figure 3 follows a clockwise path around the origin and is a collapsing Lissajous. Eclipses are possible when JWST's trajectory is within the Moon's orbit projection on the RLP-YZ plane, appearing as potential intersections, shown in the upper left and lower right areas of the plot. In time, that condition occurs about 4 times in the 13 month simulation. As the orbit period around the L2 point is about 6 months, a close approach occurs every 3 months starting around January 2019. Only in the bottom right region is JWST close enough in time/space to the Moon to experience an eclipse.

This proximity is clarified in Figure 4, a time history plot of the Sun-Vehicle-Moon (SVM) and Sun-Vehicle-Earth (SVE) angles during the 13-month period of interest. The plot shows the SVE angle in blue and the SVM angle in red, with a horizontal line showing the eclipse threshold of 2 deg for Moon and 1 deg for Earth. Due to the relative diameters of the Earth and Moon and the Sun to JWST distance, angles below this limit have a high probability of eclipses. The SVE angle never violates the threshold, so there are no eclipses caused by the Earth in this baseline case, as expected from viewing Fig. 3. Only during late September does the SVM angle exceed the limit, indicating a Moon eclipse of JWST. This is the eclipse for which avoidance strategies will be examined in this paper. However, before the trade studies are discussed, the JWST attitude and thrust direction constraints must be factored in, as described in the next section.

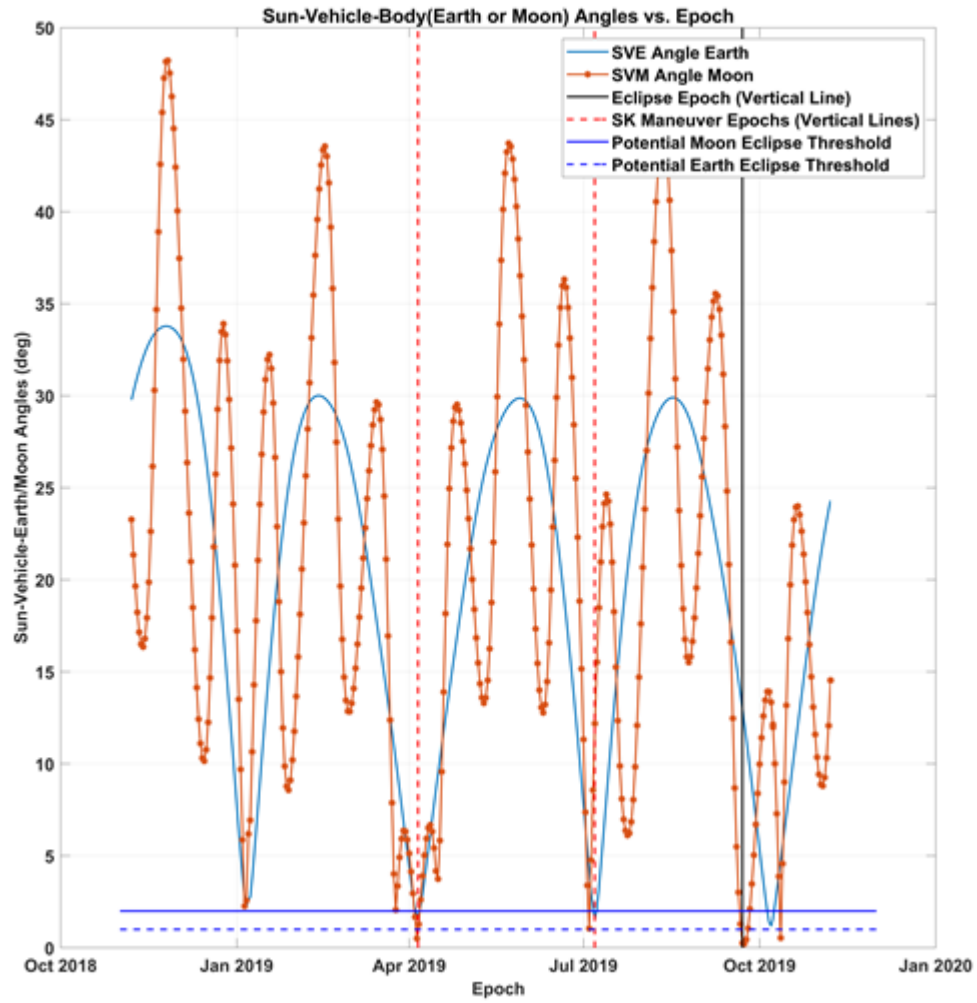


Figure 4. Baseline Sun-Vehicle-Earth (SVE) and Sun-Vehicle-Moon (SVM) Angles vs. Epoch.

JWST Science Mission Attitude Restrictions during Thrust Maneuvers

JWST's science instruments require thermal stability, driving the location and pointing of thrusters so that thrust plumes are on the sunward side of the Observatory, as well as constraining the attitude so that the instruments are never illuminated. The combination of these constraints results in JWST being unable to maneuver in the Sunward direction. During the mission science orbit, any thrust event, including momentum unloads, station keeping maneuvers and the proposed eclipse avoidance maneuver must meet angle constraints which are represented by JWST spacecraft Euler rotations (Sun pitch, roll). Sun yaw is the final rotation that fulfills the set and is not constrained. Figure 5 shows the representation of Sun angles to a commonly used body fixed frame with labels J1, J2, and J3. The next section will detail how these attitude rotations map onto the SEM RLP frame used in this analysis.

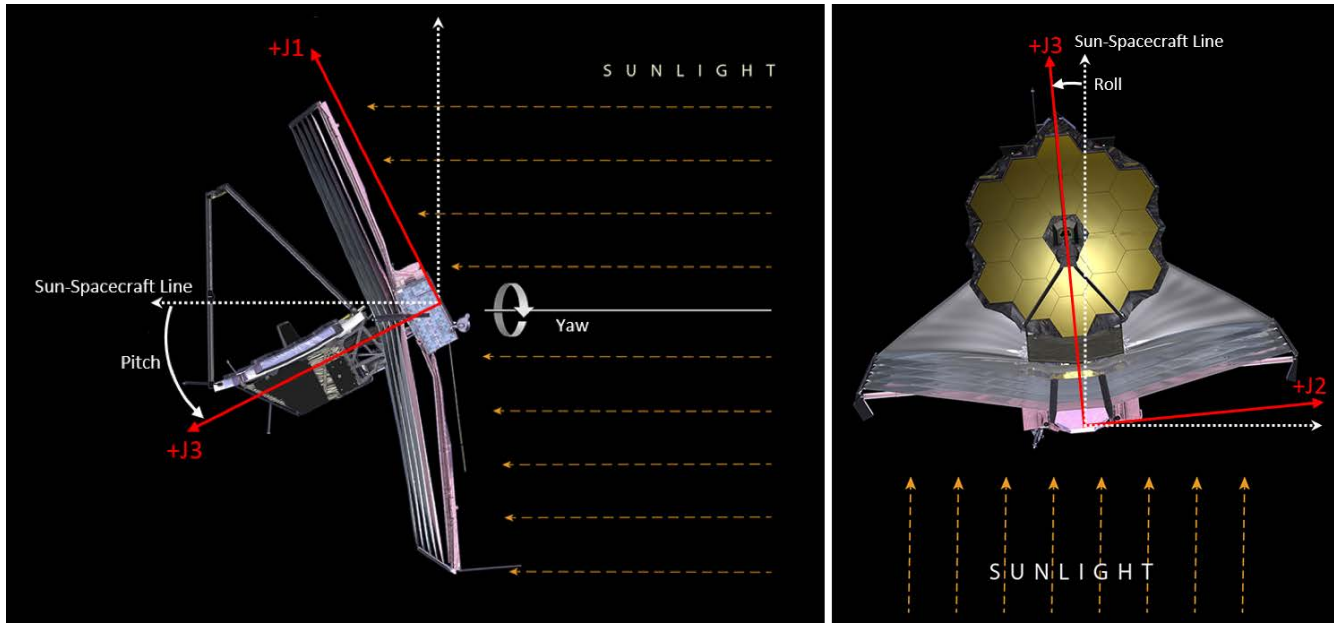


Figure 5. Relationship of Body Axes (J1, J2, J3) to JWST Sun Yaw/Pitch/Roll Angles

To convert from Sun angles to the SEM RLP frames, the angles are converted through intermediate reference frames in the following order: Sun angles to JWST body frame (J1, J2, J3) to Modified Julian 2000 (MJ2000) inertial frame to SEM RLP frame. The conversion from Sun angles to the fixed JWST body frame vectors are defined relative to the Sun to spacecraft vector in Figure 5. The +J3 vector starts in alignment with the Sun-spacecraft vector. A 3-1-2 Euler rotation sequence then rotates JWST into a chosen attitude. The first rotation, the Sun yaw, is a counter-clockwise rotation in the J2 and J1 plane with the J3 / Sun-spacecraft vector pointing into the page. The second rotation, the Sun roll, is a counter-clockwise rotation in the J3 and J2 plane with J1 pointing out of the page. The last rotation, the Sun pitch, is a counter-clockwise rotation in the J3 and J1 plane with J2 pointing into the page. Once the rotation is in the body frame, a direction cosine matrix is generated for the body frame to MJ2000 frame and the MJ2000 to SEM RLP frame at the maneuver epoch. These two transformations make the final mapping of restricted thrust directions into the SEM RLP frame.

With this attitude definition, JWST attitude restrictions are defined in the Sun Yaw/Pitch/Roll: Yaw: $[-180, 180]$ degrees, Pitch: $[-53, 0]$ degrees, and Roll: $[-5, 5]$ degrees. Applying these restrictions with a resolution of 1 degree for each rotation angle, Figures 6, 7, 8, and 9 map JWST allowable maneuver directions as unit vectors in the SEM RLP frame. Figure 6 shows the allowable attitude limits in a 3-D plot, and in each RLP 2D plane, showing the complexity of mapping the attitude constraints within the RLP frame. Figures 7 through 9 show the allowable Sun Pitch, Sun Roll and Sun Yaw unit vectors in the RLP-YZ plane. Note that the color gradient is for illustrative purposes only.

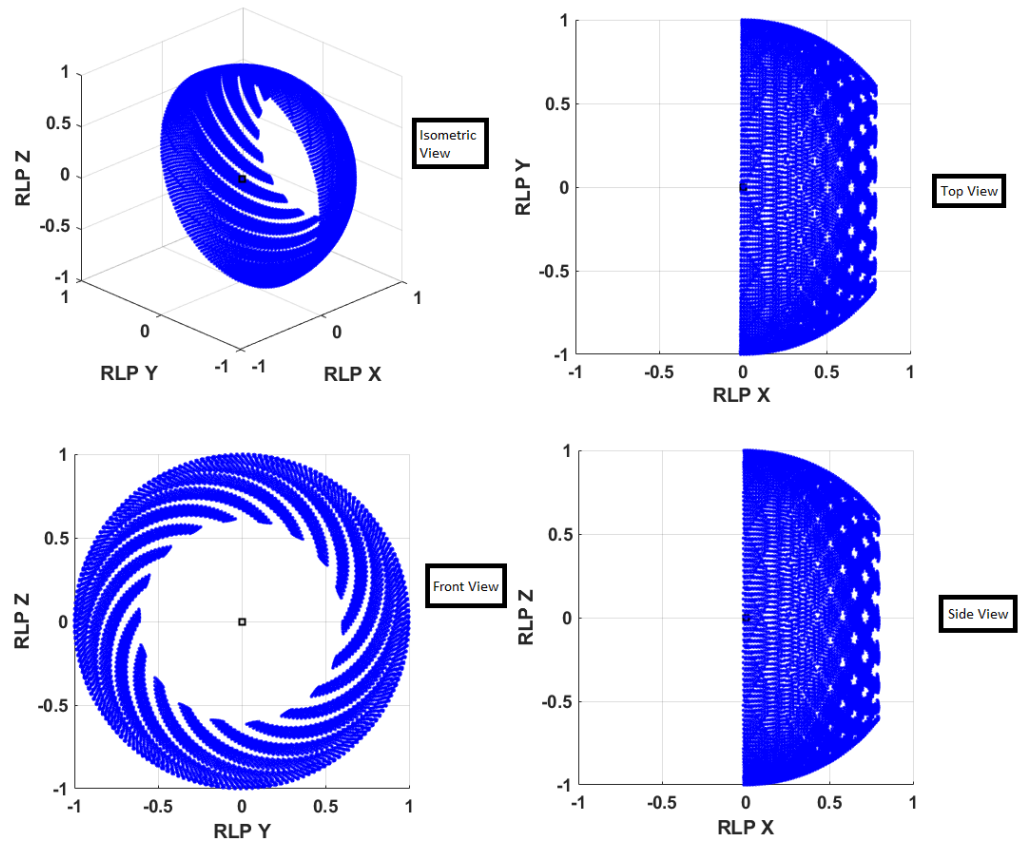


Figure 6. Unit Vector JWST Allowable Maneuver Directions in the RLP frame with Multiple Views

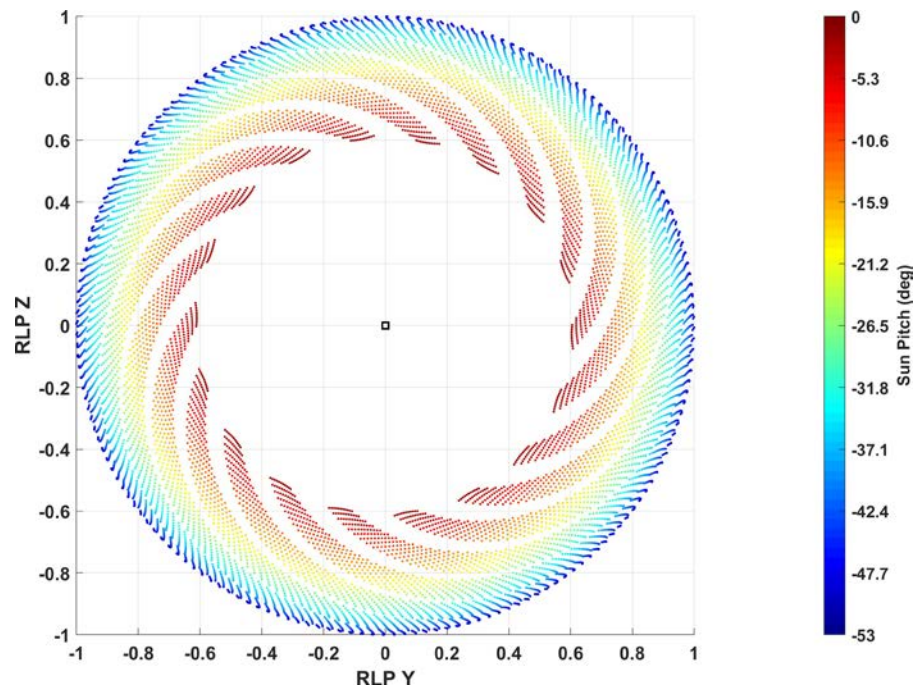


Figure 7. Sun Pitch in RLP-YZ Plane: Allowable Maneuver Directions

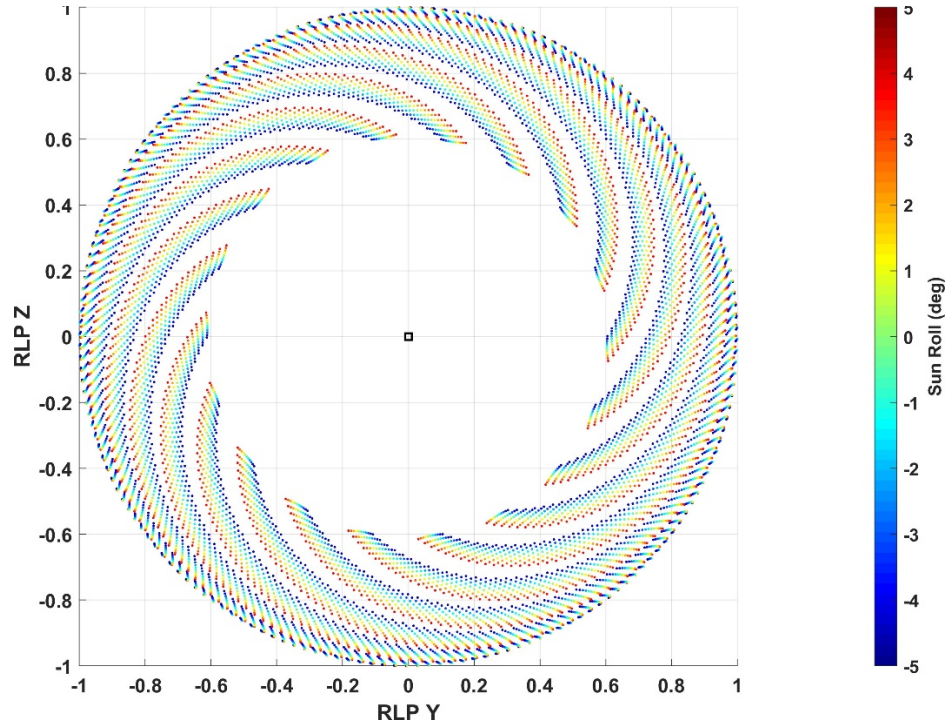


Figure 8. Sun Roll in RLP-YZ Plane: Allowable Maneuver Directions

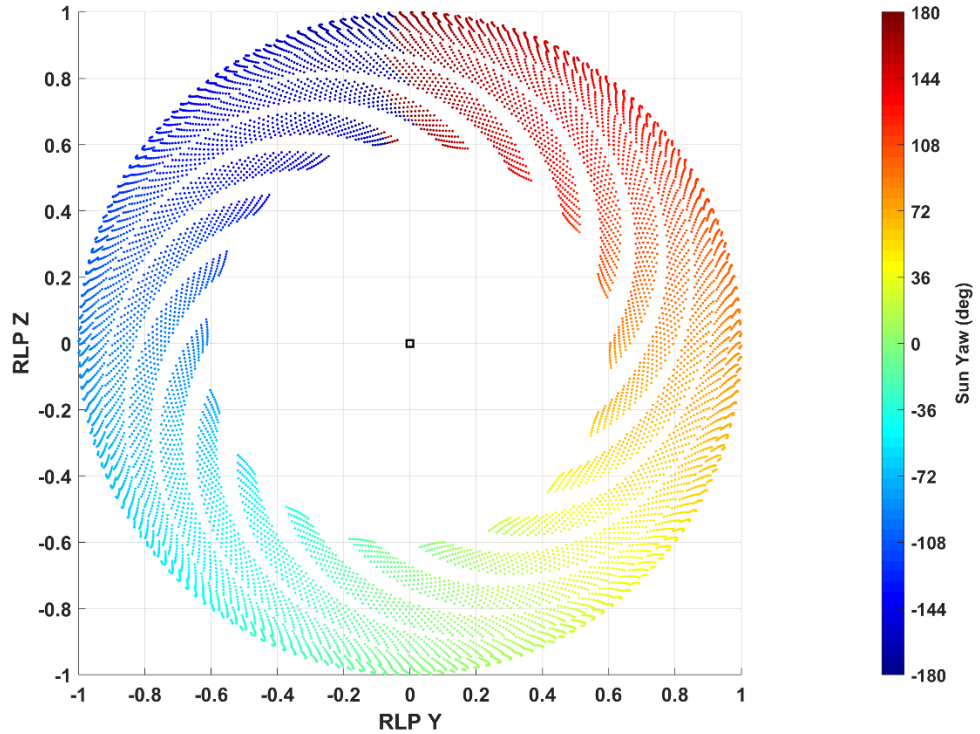


Figure 9. Sun Yaw in RLP-YZ Plane: Allowable Maneuver Directions

The JWST maneuver direction is significantly limited in the RLP-X direction. Maneuvers are restricted to approximately 37 degrees off the +RLP-X axis and about 90 degrees off the -RLP-X axis. The limitation can cause the dV cost in the science orbit to increase significantly since energy-reducing maneuvers are not efficient with the thrust direction constraints. For both RLP-Y and RLP-Z directions, JWST can thrust in those directions within requirements.

METHODOLOGY

For this study, the force model consists of multibody point masses, solar radiation pressure (SRP), and Earth non-spherical harmonics. Celestial bodies are treated as point masses and include Sun, Moon, Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. The JWST spacecraft is modeled as a sphere with a mass of 6310 kg, a solar radiation pressure (SRP) area of 161 m², and a solar reflectivity coefficient of 1.8. Finally, though it has a lower impact on the JWST trajectory in its operational orbit than other forces, Earth non-spherical harmonics are modeled with a 21x21 degree and order.

The maneuver design itself also consists of a few key model assumptions: impulsive maneuvers, no momentum unloads modeled, and the applied attitude restrictions to only the eclipse avoidance (EA) maneuver and not the station keeping (SK) maneuvers.

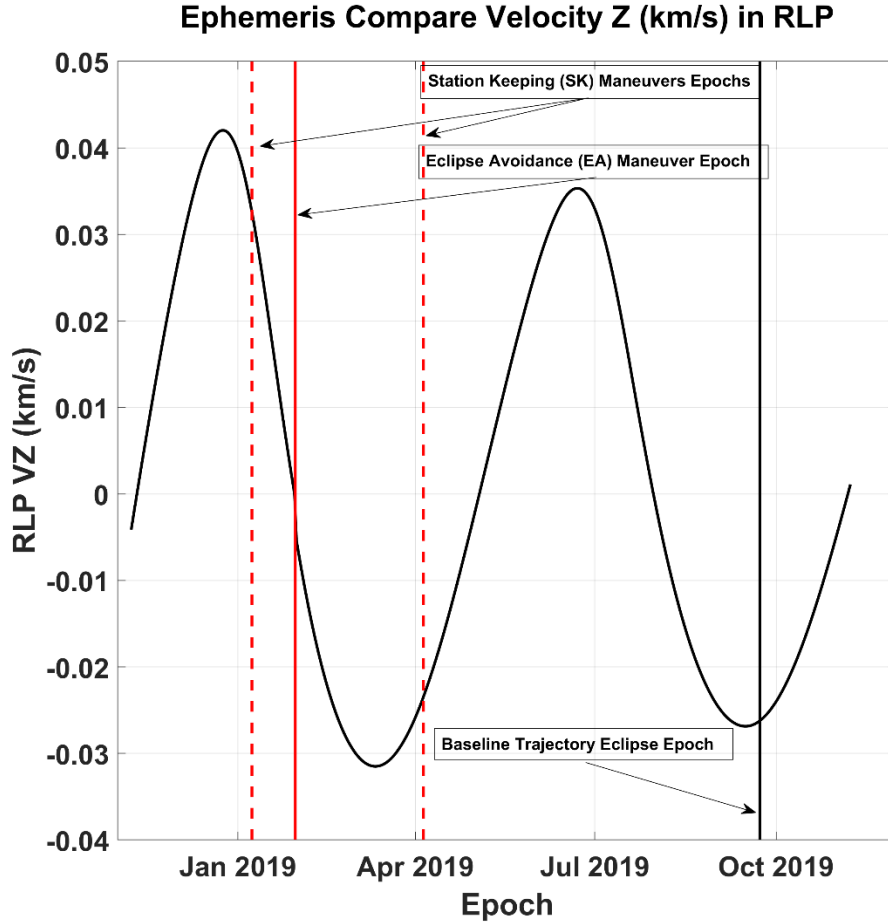


Figure 10. Baseline Trajectory of RLP Vz vs. Epoch with Marked Maneuver/Eclipse Events

Figure 10 illustrates the maneuver plan baseline used to generate each trade in this study. The maneuver plan consists of 3 propulsive maneuvers: SK to EA to SK. As JWST has not been formally studied for eclipse avoidance, this paper focuses on characterizing the trade space that, as a next step, a differential corrector or other numerical optimization scheme would target an EA maneuver to avoid an eclipse. With this objective in mind, the EA in this paper is a non-targeted maneuver that will destabilize the libration orbit in an attempt to avoid the late September 2019 eclipse. The SK maneuvers prior to and after EA are targeted differential correction solutions to stabilize the libration orbit. The SK maneuvers are all located where RLP-Y = 0 and are maneuvered in the +RLP-X direction, except when stated otherwise. Metrics measuring the delta-V (dV) used for these maneuver plans consist of only these three maneuvers. In a full JWST trajectory design, additional SK maneuvers would be included to maintain the libration orbit

beyond the timespan shown. The next section describes each of the seven trade space studies, one preliminary study and two groups of three studies.

First, a preliminary study is explored with prior literature on the maneuver location and burn direction for eclipse avoidance with a test maneuver (magnitude set to 10 m/s and in the negative component direction). A group of 3 more formal studies using unconstrained JWST EA maneuver directions follows, with the first formal trade study looking at a fixed EA location/direction, while varying the burn magnitude of the EA between -20 and 20 m/s. The metrics evaluate if the resultant trajectories avoid eclipses and their dV cost. The second trade study chooses a successful EA maneuver from the first trade study and varies the epoch of the follow-on SK maneuver. This explores lower cost SK maneuvers that still avoid eclipses. The third unconstrained attitude study looks at how early an EA maneuver can be performed prior to an eclipse. This is measured in orbit half revolutions counted at crossings of the RLP-X axis. The four prior trade studies are all made without constraints on thrust direction. The final set of three trade studies repeats the 2nd-5th trades for a JWST constrained thruster direction, meeting the Sun angle requirements as shown in Figure 6. The results section concludes with metrics and observations and made on the JWST-specific trade studies.

RESULTS

Preliminary Study

Previous analyses suggest Z-axis control for libration point orbit eclipse avoidance, a process of influencing the spacecraft trajectory's RLP Vz component by maneuvering along the RLP-Z axis by Pernicka, and additionally at a burn location when RLP Vz = 0 m/s by Roberts for the Advanced Composition Explorer (ACE) mission.^{4,7,11} Cavaluzzi adds an operationally constrained maneuver strategy with the Wilkinson Microwave Anisotropy Probe (WMAP) mission that uses the RLP Vy = 0 m/s burn location but maneuvers in the RLP Vx direction.⁵ Both strategies are examined in this preliminary study using a fixed maneuver magnitude of 10 m/s. As the projection of the eclipse region is primarily defined by the RLP Z and Y position components, maneuvers which maximize propagated change in these components is desired.¹¹ In this case, both RLP Z and Y are represented by SVE and SVM angles. The scope of this paper is for this baseline trajectory, and further work is required to trend this maneuver strategy for other trajectories. Figure 11 shows the results of the RLP Vz direction control strategy on the baseline case trajectory, while Figure 12 shows the effects of the RLP Vx direction control strategy. Both Figure 11 and Figure 12 are truncated the y axis between 0 – 20 degrees for better readability of the results.

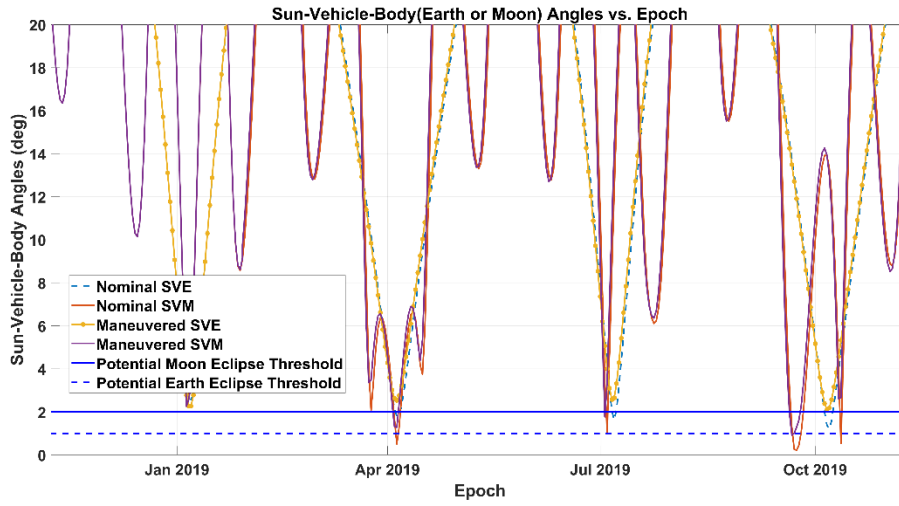


Figure 11. Effects of RLP V_z direction Control Strategy on Baseline Trajectory: EA maneuver at RLP $V_z = 0$, 10 m/s in the $-V_z$ direction

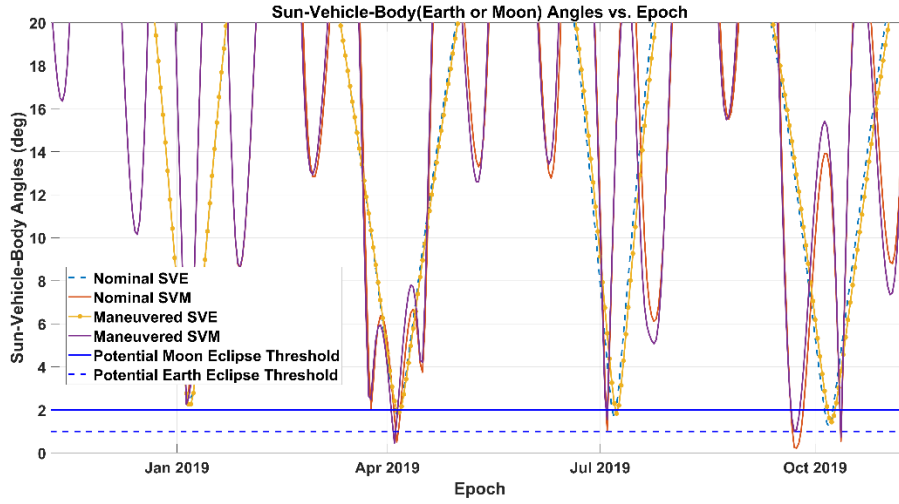


Figure 12. Effects of RLP V_x strategy on SVE and SVM angles: EA maneuver at RLP $V_y = 0$, 10 m/s in the $-V_x$ direction

The eclipse from the nominal case study can be seen for the predicted Moon eclipse in late September 2019. Though the angles cross the threshold at periodic times throughout the simulation, both maneuver strategies result in a trajectory with no detected eclipses. For the predicted Moon eclipse, the maneuvers increase the SVM angle by about 0.75 deg. The RLP $V_y = 0$ maneuver strategy is more effective for the local SVE angle minima in October 2019, increasing it by an additional degree compared to the RLP $V_z = 0$ strategy. Even with this difference, the results are qualitatively similar for both plots and both maneuver strategies in avoiding the eclipse from the Moon. However, the JWST attitude constraints as seen in the previous section preclude maneuvers directly along the RLP-X axis; thus the $V_y = 0$ strategy will result in significant dV costs which could reduce the mission lifetime. For the $V_z = 0$ case, this results in a dV cost of 13.6 m/s (3.5 m/s for SK) while the $V_y = 0$ strategy results in a dV cost of 52.5 m/s (42.5 m/s for SK). Thus, for the rest of this paper, the RLP $V_z = 0$ burn location and RLP V_z direction maneuvers were chosen to search for successful eclipse avoidance maneuvers.

Unconstrained JWST Thrust Direction Trade Studies

Using the Vz maneuver strategy from the prior section, the following unconstrained thrust direction trade studies encompass three independent variables: EA maneuver magnitude, following SK maneuver epoch, and EA maneuver relative start epoch prior to the eclipse.

The first trade study fixes the EA maneuver at the burn location RLP $V_z = 0$ and in the RLP Vz direction approximately 3 RLP-X axis crossings prior to the detected eclipse. The study varies the EA maneuver from -20 m/s to +20 m/s along the RLP-Z axis in increments of 0.2 m/s. The preceding SK maneuver to the EA maneuver occurs in the same location as the nominal case. The following station keeping maneuver will occur at the propagated burn location when RLP $Y = 0$.

The burn locations and resulting trajectory in this study shows that, in Figure 13, an EA maneuver in the RLP-Z direction changes the trajectory so that JWST successfully avoids the September lunar eclipse. The baseline trajectory (EA maneuver magnitude equals 0 m/s) centers the trade study, and the total delta-V cost increases as the EA maneuver is increased up to 20 m/s in the +/- RLP-Z directions. The minimum EA dV that successfully avoids the eclipse has a magnitude of 4.2 m/s in the RLP-Z direction, or in shorthand, 4.2 m/s +RLP-Z. The total ΔV cost for that 3-maneuver scenario is 5.5 m/s (4.2 m/s for EA + 1.3 m/s for SK maneuvers).

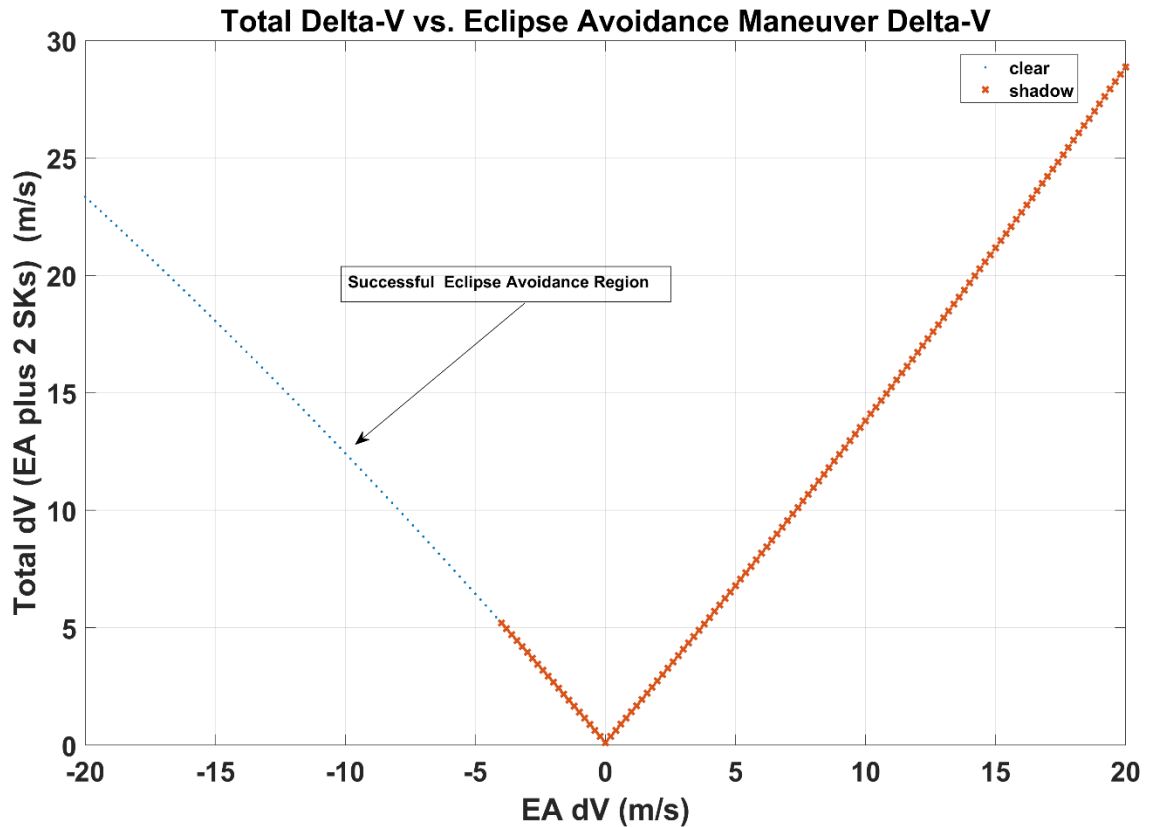


Figure 13. Unconstrained Thrust Direction with Variable EA Magnitude: EA dV vs. Total dV Cost

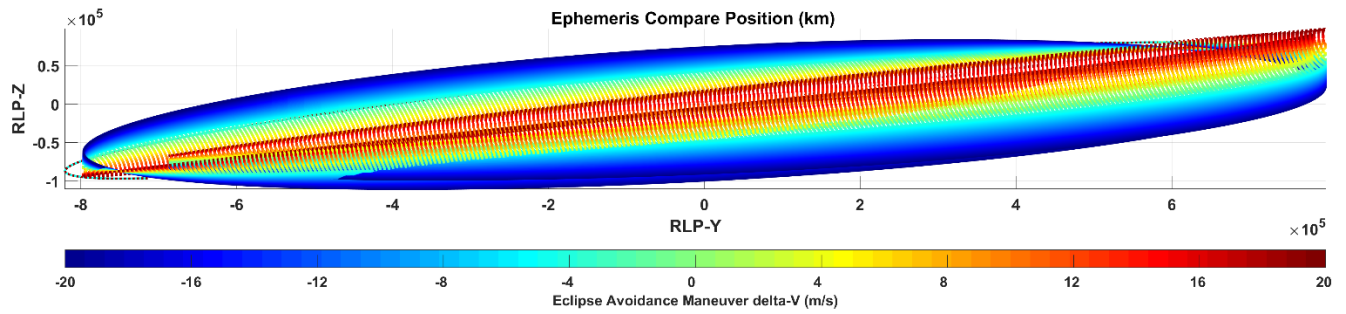


Figure 14. Unconstrained Thrust Direction: Propagated Trajectories in the RLP-YZ plane.

Figure 14 represents the resultant 13-month trajectories in the RLP-YZ plane, with one case being the case study seen in Figure 3. Red indicates a trajectory with a 20 m/s +RLP-Z EA maneuver and the trajectories shift in a color gradient to blue for a trajectory with a 20 m/s EA in the -RLP-Z direction. The EA maneuver occurs in January 2019, about 8 months (three RLP-X-axis crossings) prior to the original predicted eclipse. The propagated trajectories in Figure 14 all travel clockwise around L2, with the same region of potential Moon eclipse as described by the baseline case study orbit shown in Figure 3. Another subset of trajectories will experience Earth eclipse(s) as they cross the Earth shadow at the center of the RLP YZ plane.

The evolution of the SVE and SVM angles are depicted in Figures 15 and Figure 16 respectively; it can be seen from these two plots that violations of SVE and SVM eclipse constraints occur. Figure 15 for Sun-Vehicle-Earth has a few families of orbits that have local minima in April, July, and October 2019. Each of these minima result in an Earth eclipse for a subset of the trade study. For values less than or equal to -4.2 m/s, there are no Earth eclipses. Between -4.2 m/s and 8.2 m/s EA maneuvers, there are no Earth eclipses (only Moon). Between 8.2 m/s to 11.8 m/s, the October 2019 minima results in an Earth eclipse. Between 11.8 m/s to 16 m/s, there are eclipses in July and October. Finally, Earth eclipses during all three local minima occur when the maneuver is greater than 16 m/s. For Moon eclipses in Figure 17 for Sun-Vehicle-Moon angles, there are local minima in March, April, July, September and October 2019. As seen however in Figure 3, the Moon needs to be at the correct state and time relative to JWST to cause an eclipse. As a result, the trends change relative to the Earth results. For trade study values less than or equal to -4.2 m/s, there are no Moon eclipses. Between -4.2 m/s and 1.8 m/s EA maneuvers, only the September eclipse occurs. Between 1.8 m/s and 2.4 m/s, local minima from September and October cause an eclipse. Between 2.4 to 5.8 m/s, April, September, and October have lunar eclipses. From 5.8 m/s to 8.0 m/s, April, July, September, and October have lunar eclipses. All but March eclipses have appeared in the results. From here, the current eclipse regions begin to drop off. At a trade study EA maneuver of 8.2 m/s, both October and September eclipses are gone, leaving JWST with April and July eclipses. By 12 m/s, only lunar eclipses in July are left. By 14.4 m/s EA maneuvers, there are no lunar eclipses. The March lunar eclipse then appears at a trade study value of 16.8 m/s and continues to the end of the trade study at 20 m/s. Earth and Moon eclipses overlap when the +RLP-Z component maneuvers are applied and are periodic based on JWST's case study orbit around L2 of 6 months.

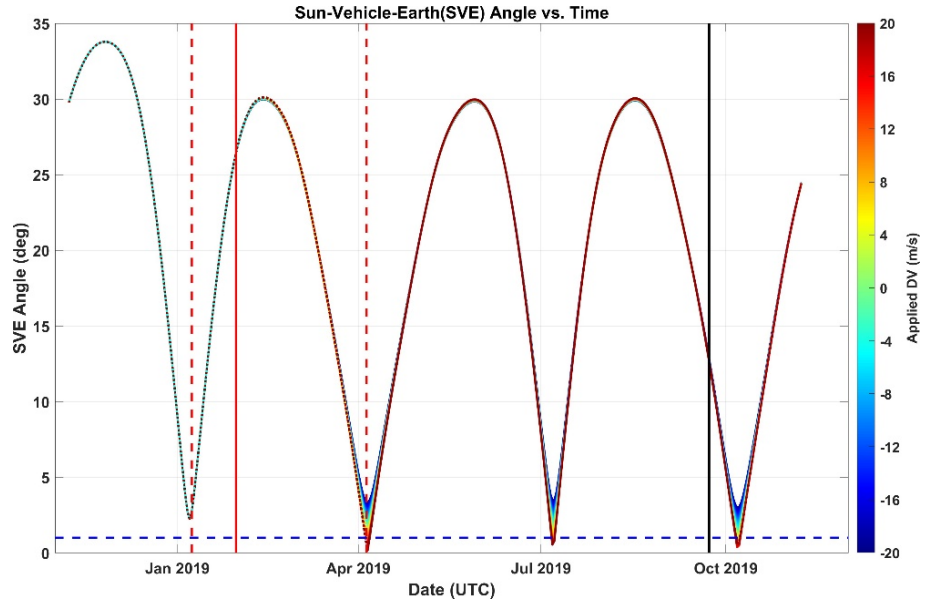


Figure 15. Unconstrained Thrust Direction: SVE Angle vs. Epoch for 13 months.

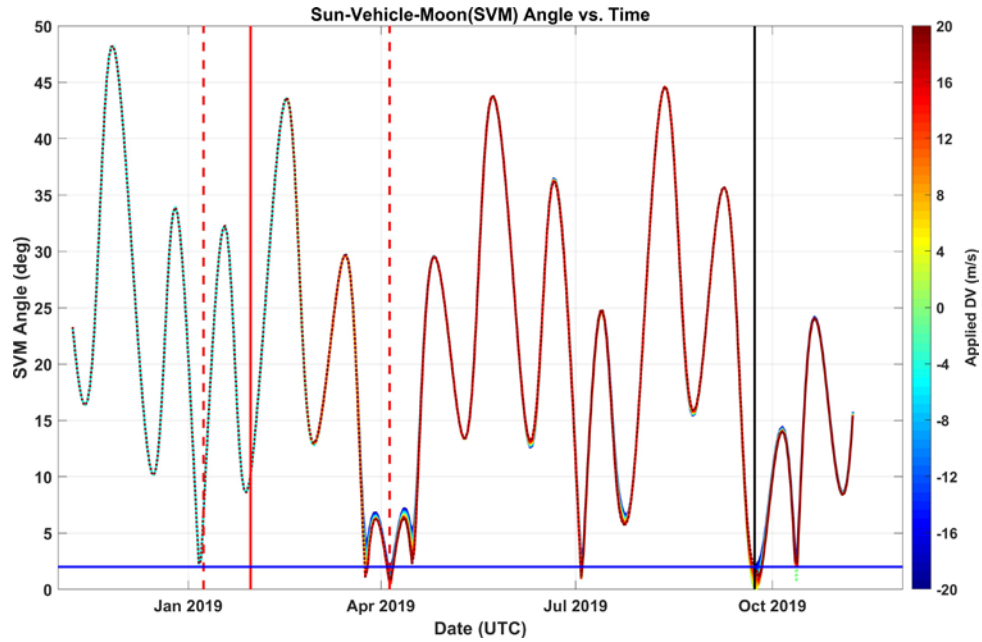


Figure 16. Unconstrained Thrust Direction: SVM Angle vs. Epoch for 13 months.

The EA dV magnitudes examined in this study are large for JWST's propellant budget. A 20 m/s EA maneuver would expend the equivalent of 80% the propellant required to maintain the orbit at L2 for 10.5 years. While there is some margin in the propellant allocation, this would preclude performing an extended mission or being able to resize the LPO to meet changing science constraints. However, the avoidance of a deep Earth annular eclipse would make this expenditure worthwhile, since a 90% obscuration even for a short time would adversely affect the power margin, or could even terminate the mission from a power perspective if it lasted longer than 3 hours. This scenario is very unlikely, but it is wise to prepare for contingencies prior to launch.

Varying Follow-On SK Maneuver Epoch after Successful EA Maneuver

The next trade study looks at the timing of the first SK maneuver following an EA maneuver by varying the SK burn epoch. A successful EA maneuver trajectory from the previous trade study results, with an EA of 4.2 m/s in the + RLP-Z direction was selected as the starting point for this analysis. The follow-up SK maneuver occurred nominally at RLP Y = 0 km, 66 days after the EA maneuver. For this trade analysis, the SK epoch was varied from 1 day to 90 days after the EA maneuver; the rest of the conditions are the same as the previous trade study.

Figure 17 shows the total delta-V cost versus SK epoch offset after the fixed 4.2 m/s +RLP-Z EA maneuver. As seen in the plot, the libration orbit can be maintained with a SK maneuver for the full span of epoch offsets, but only a small portion of trajectories during that span result in successful eclipse avoidance. SK maneuvers which occur earlier than 49 days after the EA will counteract the effects of the EA maneuver enough so that the lunar eclipse of JWST still occurs. SK maneuvers later than 74 days after EA do not maintain the libration point orbit outside the eclipse region and the spacecraft will fall back into the region of lunar eclipse. For this particular eclipse case, decreasing the time between the EA and follow up SK to 50 days results in a total dV cost of 4.9 m/s, with the minimum of 0.7 m/s needed for the SK follow-on maneuver. Note that the nominal SK dV for this maneuver was This is rather large in magnitude for an L2 LPO SK maneuver; optimization of the SK and EA maneuvers would occur in real JWST operations.

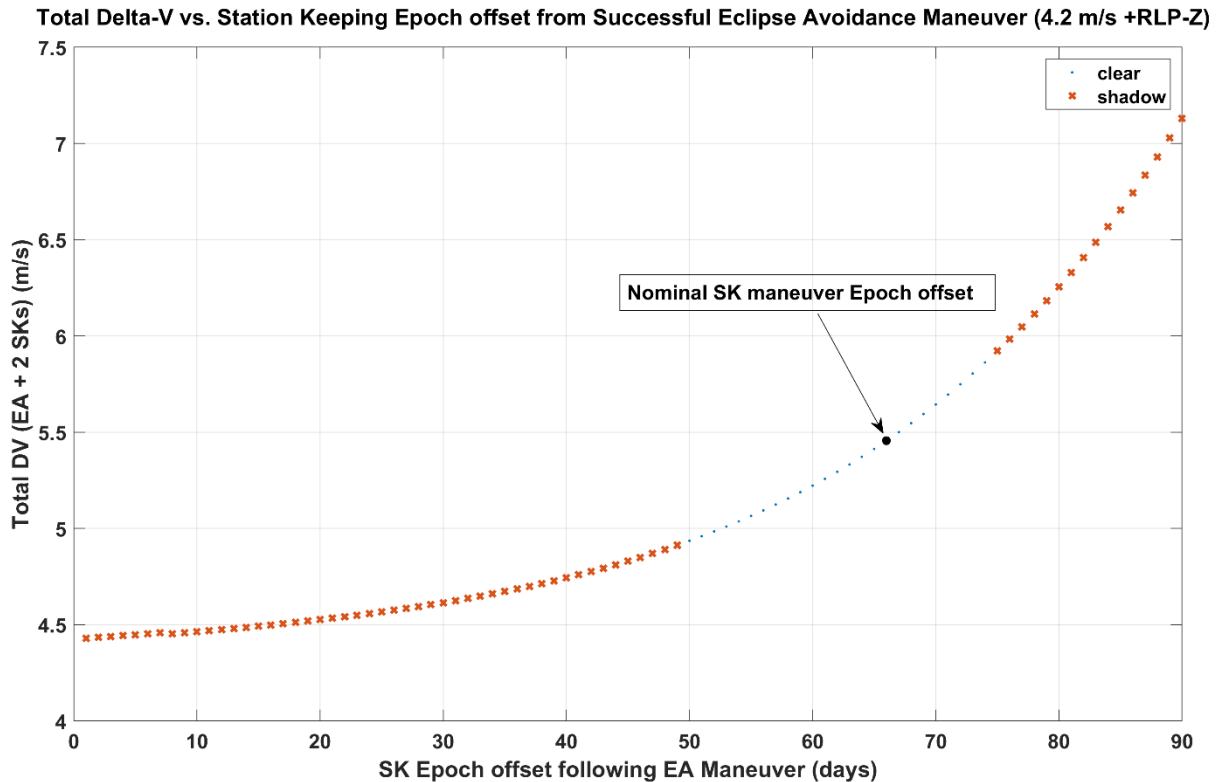
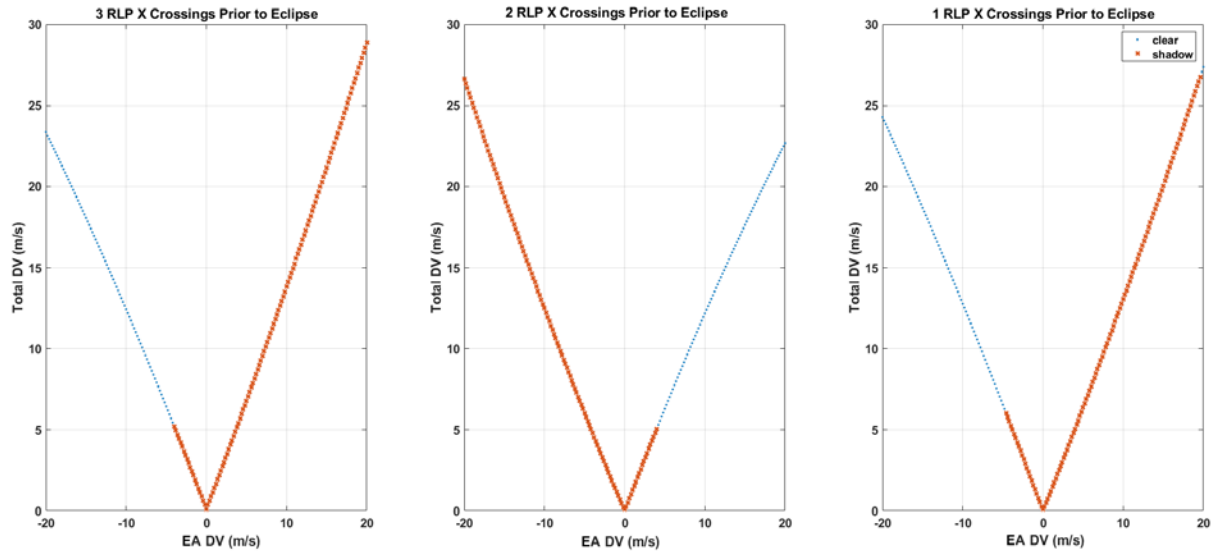
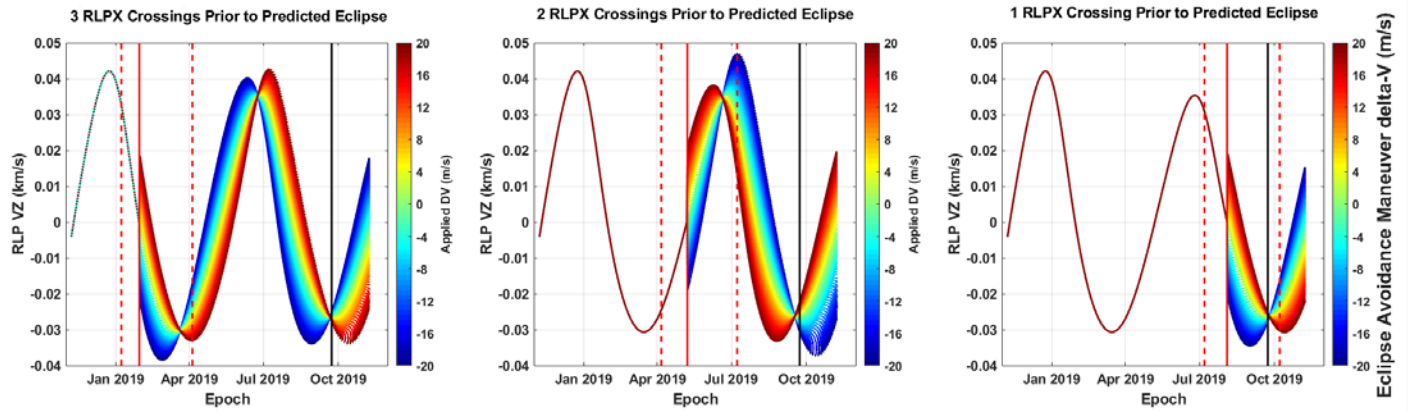


Figure 17. Unconstrained Thrust Direction of SK Epoch Offset Trade Study
Total DV Cost (EA+SK) vs. SK Epoch offset.

Varying Start of EA Maneuver Strategy Relative to the Eclipse



**Figure 18. Unconstrained Thrust Direction of RLPX Crossings Trade Study
Total Delta V Cost (EA and SK) vs. EA Delta-V.**



**Figure 19. Unconstrained Thrust Direction of RLPX Crossings Trade Study
Compare Ephemeris RLP Vz (km/s) vs. Time.**

The third trade study varies the start of the EA maneuver strategy. As the conditions repeat every half rev around the libration orbit (RLP-X axis crossings), the maneuvers are tested after each crossing. The prior runs all perform the maneuver plan 3 RLP-X crossings prior to the eclipse. Repeating the first trade study of delta-V for 2 and 1 RLP-X crossings reverses the EA maneuver magnitude, as seen in Figure 18. The orientation of the trajectory to each crossing inverts after each RLP-X crossing as it crosses either the +RLP-X and -RLP-X axis around the L2 point, seen in Figure 19.

At the threshold where an EA maneuver results in a successful eclipse avoidance with minimum dV, the location of the EA maneuver has impact. The 5.3 m/s total delta-V cost at 3

RLP-X crossings prior to the eclipse is greater than the same case for 2 RLP-X crossings (5.1 m/s) and is less than the 1 RLP-X crossing plot (5.8 m/s). The 3 RLP-X crossing case has the same EA maneuver cost as the 2 RLP-X case of 4.2 m/s; it just has a larger SK cost of 0.2 m/s. For the 1 RLP-X case, a successful EA maneuver of 4.8 m/s is needed with an SK cost of 1.0 m/s.

In operations, the recognition and planning of an EA maneuver would most likely happen years prior to the detection, as it can be predicted by propagating the definitive state from ground station tracking. A maneuver performed at equal to or more than 2 RLP-X crossings is desired in case another maneuver is needed as contingency. In this case, a maneuver centered on a 2 RLP-X crossing condition would be desired to minimize fuel use.

Overall, for a minimum total delta-V cost, a successful EA maneuver of 4.2 m/s in the +RLP-Z direction can be performed 2 RLP-X crossings prior to the detected eclipse with a follow on SK maneuver 45 days after the EA maneuver. The total delta V cost in this case study orbit was 5.1 m/s.

Constrained JWST Attitude Trade Studies

The prior three trade studies (the 5th-7th studies) do not constrain the JWST thruster attitudes as shown in Figure 6. These three studies repeat the process but with chosen attitude rotations that correspond to the colored asterisk marks in Figure 20. The selection criteria was selecting the Sun angle Euler rotations from Figure 5 with the maximum +RLP-Z unit vector and the rotations to the maximum -RLP-Z unit vector. The resultant Sun angle Euler rotations equate to (178 yaw, -53 pitch, 5 roll) degrees for +RLP-Z and (-2 yaw, -53 pitch, -5 roll) degrees for -RLP-Z maneuvers. The unit vectors (\mathbf{Z}_P for +RLP-Z and \mathbf{Z}_N for -RLP-Z maneuvers) are stated in Equations 1 and 2.

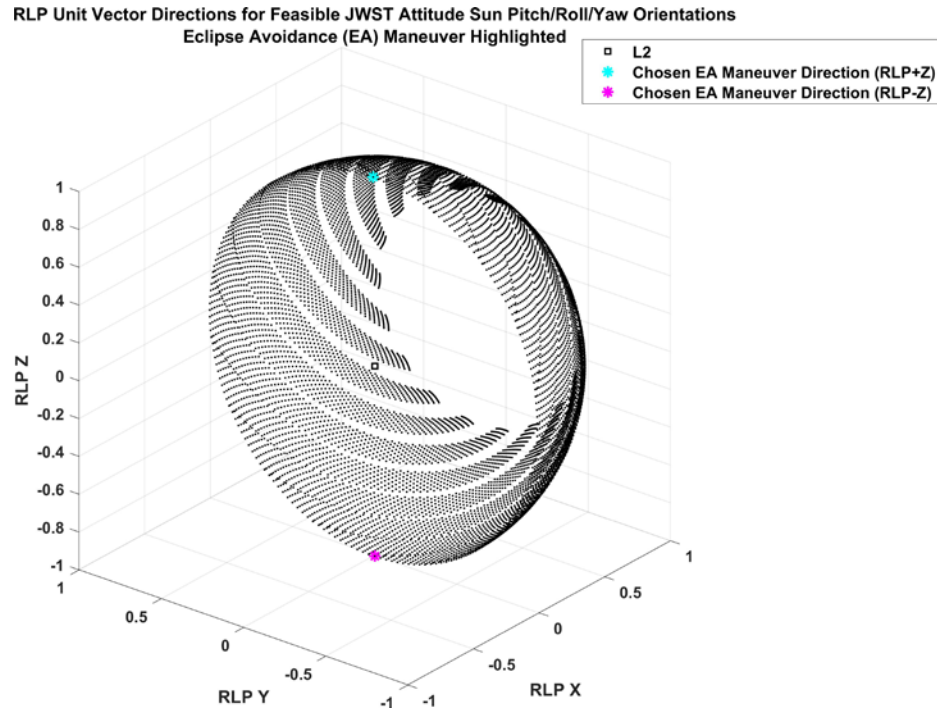


Figure 20. RLP Feasible JWST Unit vectors with the JWST RLP +/- Z Eclipse Avoidance Maneuvers Highlighted

$$\mathbf{Z}_P = -0.00424\hat{i} + 0.00545\hat{j} + 0.99998\hat{k} \quad (1)$$

$$\mathbf{Z}_N = -0.00557\hat{i} + 0.00541\hat{j} + -0.99997\hat{k} \quad (2)$$

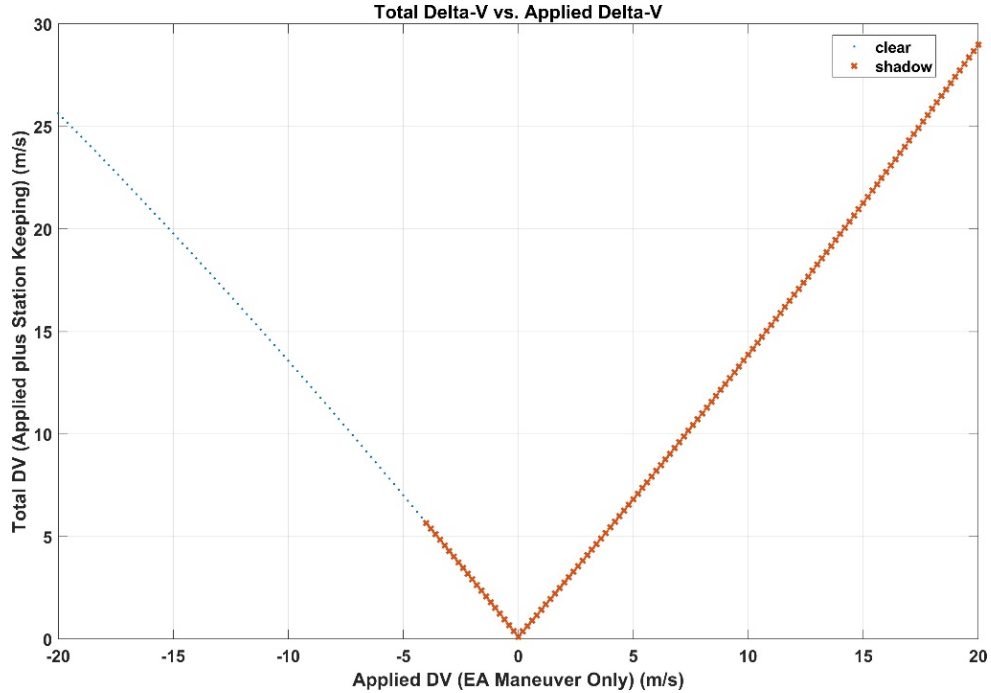


Figure 21. Constrained Thrust Direction with Variable EA Magnitude: EA dV vs. Total dV Cost

With these chosen JWST Sun yaw/pitch/roll configurations, the trade studies are repeated. The delta-V trade study result is displayed in Figure 21. A similar trend from Figure 13 is seen here, but the attitude restrictions cause an increase in total delta V costs for SK maneuvers. The EA maneuver magnitude of 4.2 m/s in the -RLP-Z is a minimum total delta V for a successful eclipse avoidance; the total delta V increased by 0.4 m/s to 5.9 m/s (4.2 m/s for EA + 1.7 m/s for SK maneuvers). At a 20 m/s -RLP-Z applied EA maneuver, this disparity is increased from 23.4 m/s in Figure 13 to 25.6 m/s in Figure 21, a 2.2 m/s increase. With the SK prior to the EA maneuver staying consistent, this increase in total delta V for the same EA maneuver is due to the follow up SK maneuver costs. The next study focuses on this SK maneuver by repeating the SK epoch off trade study in Figure 22. The same trend in Figure 22 occurs as Figure 17. The cost for the same delay (66 days) for the SK maneuver increases by the same 0.4 m/s as in the trade study. Moving the SK maneuver to 45 days after the EA maneuver decreases this gap to 0.1 m/s for a total delta V cost of 5.0 m/s in Figure 17.

The third trade study repeated for JWST attitude constraints is displayed in Figure 23 to perform the EA maneuver RLP-X crossings before the eclipse detection. Between the unconstrained and constrained cases, the overall delta V costs for the minimum values of each plot increases 0.2 m/s for 2 crossings and to 0.4 m/s for 1 crossing prior to eclipse. At the end of the trade study, that difference goes up to 2 m/s for the 1 crossing plot. Overall, for a minimum total delta V cost, a successful EA maneuver of 4.2 m/s in the +RLP-Z direction can be performed 2 RLP-X crossings prior to the detected eclipse with a follow on SK maneuver 45 days after the EA maneuver. The total delta-V cost in this case study orbit was 5.3 m/s.

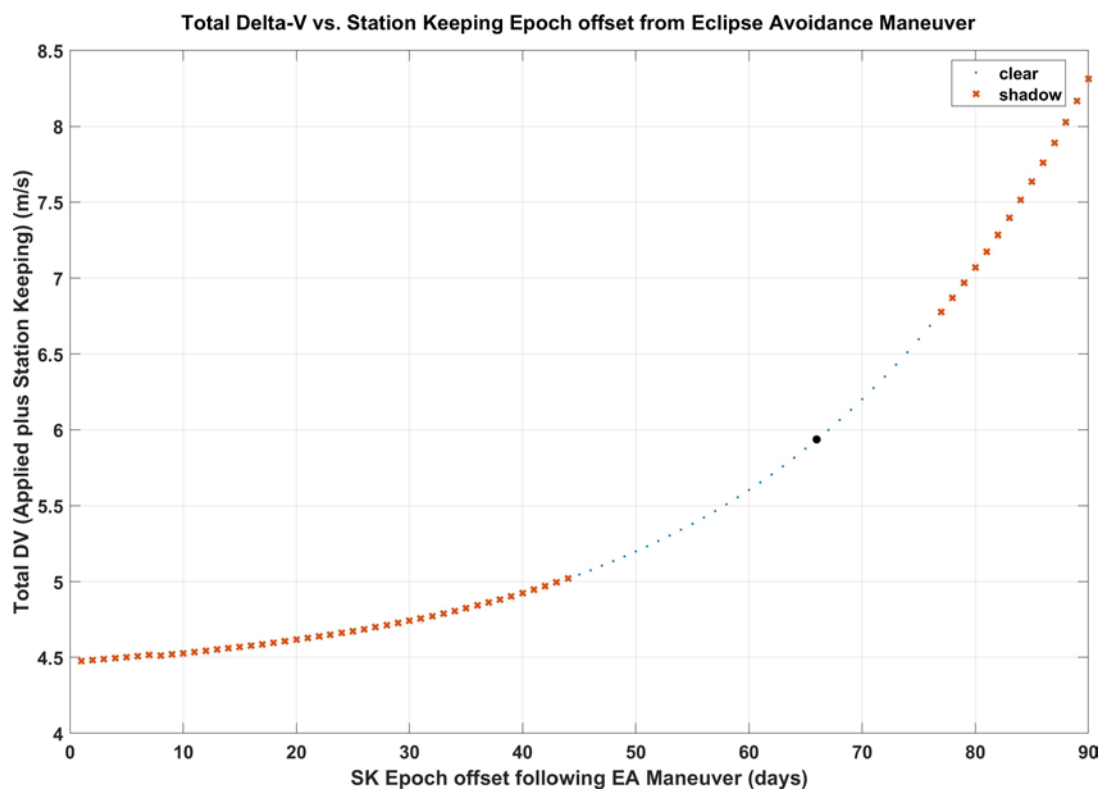


Figure 22. Constrained Thrust Direction of RLPX Crossings Trade Study Total Delta V Cost (EA and SK) vs. EA Delta-V.

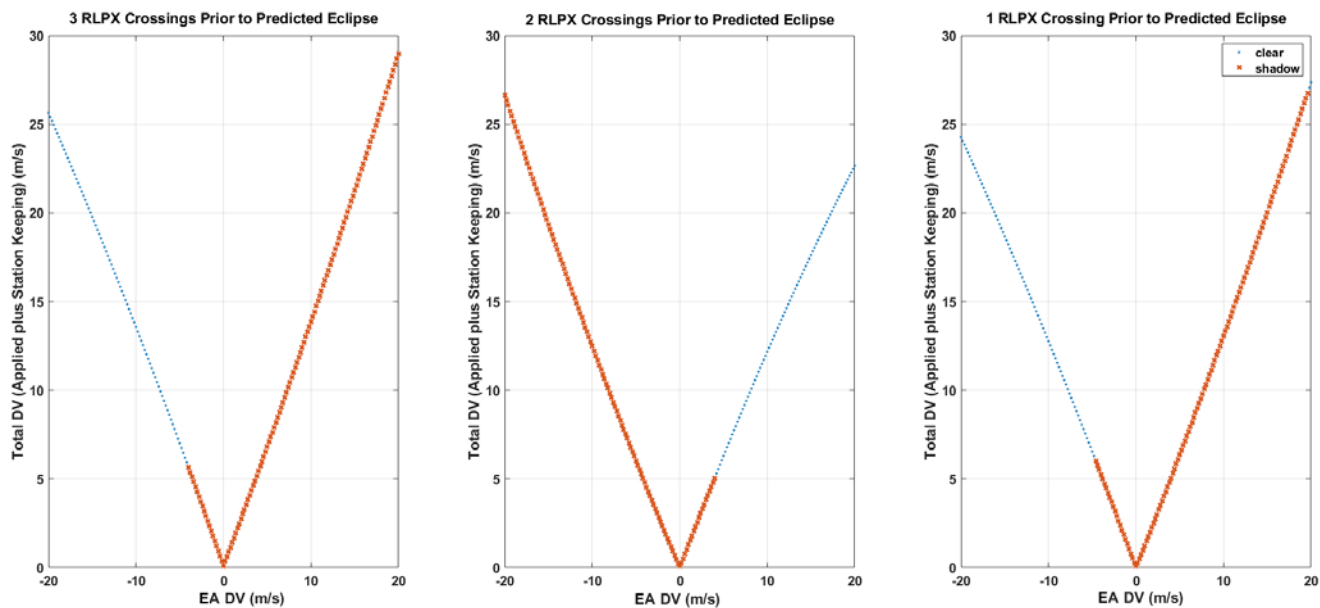


Figure 23. Constrained Thrust Direction: RLPX Crossings Trade Study: Total Delta V Cost (EA and SK) vs. Applied Delta V (EA) only.

CONCLUSION

Eclipse avoidance for a libration orbit during routine operations involves performing an additional maneuver plan to avoid an eclipse and stabilize the libration orbit. This paper studies the magnitude of the eclipse avoidance maneuver, the cost of follow on station keeping maneuvers versus its burn epoch, and the timing of the maneuver plan prior to eclipse. The first set of studies was unconstrained by the JWST attitude requirements and the second set applied JWST attitude requirements, all in a search to see if JWST has a feasible capability to avoid eclipses in a contingency.

The results found a middle ground that produces the lowest cost delta-V to perform eclipse avoidance. For an unconstrained spacecraft attitude, the total delta-V cost was 5.1 m/s (4.2 m/s + RLP-Z maneuver performed 2 RLP-X crossings prior with a follow on station keeping maneuver 45 days after). For a JWST constrained attitude, the cost goes up by 0.2 m/s to 5.3 m/s (4.2 m/s + RLP-Z maneuver performed 2 RLP-X crossings prior with a follow on station keeping maneuver 45 days after). These values, while having a direct cost on mission lifetime and are costly for lost time for science data collection, are within the fuel budget and are feasible maneuver strategies. Using these results, the objective space for an eclipse avoidance maneuver targeted can be broken down by RLP-Z direction and within 20 m/s to find the optimal low cost maneuver plan.

A series of future work topics can be explored from here. From an orbit design perspective: breaking up the maneuver plan into staging maneuvers, studying the sensitivity of the burn location $RLP V_z = 0$, and searching for optimal burn directions within the RLP XZ or YZ plane are potential research directions. For JWST design: performing the trade studies on other orbits with eclipses, applying JWST attitude restrictions on all maneuvers, adding higher fidelity solar radiation models / momentum unloads into the scenario, and performing statistical analysis on the maneuver execution and planning are other research paths.

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